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SOUTH AUSTRALIA

TECHNICAL REPORT
WSRL-0252-TR

FLIGHT TESTS OF THE MKIV WRAP AROUND FIN CONFIGURATION

R.L. POPE and R.E. DUDLEY

Approved for Public Release

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Interest in the aerodynamics of wrap around fin vehicles originated some years ago because of their applicability to the design of tube launched rockets. Weapons Systems Research Laboratory has designed and tested a number of different wrap around fin configurations. A series of five test vehicles, using a recent six finned design, has been fired from the Weapons Systems Research Laboratory 384 mm gas gun to determine flight behaviour. This report describes the trials which have been conducted and the results of analysing the data from those trials. Some comparisons are made with the results from wind tunnel tests. In general, agreement between free flight and wind tunnel measurements is good.

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S U M M A R Y

Interest in the aerodynamics of wrap around fin vehicles originated some years ago because of their applicability to the design of tube launched rockets. Weapons Systems Research Laboratory has designed and tested a number of different wrap around fin configurations. A series of five test vehicles, using a recent six finned design, has been fired from the Weapons Systems Research Laboratory 384 mm gas gun to determine flight behaviour. This report describes the trials which have been conducted and the results of analysing the data from those trials. Some comparisons are made with the results from wind tunnel tests. In general, agreement between free flight and wind tunnel measurements is good.

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1. INTRODUCTION

Interest in wrap around fin (WAF) designs was originally aroused in Weapons Systems Research Laboratory (WSRL) through an international cooperative program of research begun through The Technical Cooperation Program (TTCP). The WAF offers a simple, convenient and effective method of stabilising tube launched rockets. The original TTCP design, which had only rotational symmetry exhibited large induced rolling moments at low incidences. Such moments could easily produce undesirable flight dynamic effects such as catastrophic yaw, which would lead to serious degradations in stability and performance of a tube launched rocket. The MkI WAF design was developed at WSRL(ref.1) to minimise these large rolling moments. The design had eight fins instead of four arranged so that the configuration exhibited mirror symmetry as well as rotational symmetry in a similar way to the MkIV design in figure 1. Further improvements to the basic design led to the MkII(ref.2) and the MkIII(ref.3), both eight finned WAF designs. Flight tests of the eight finned MkIII WAF are described in reference 4. A problem with the WAF stabiliser is that the span of the fins is limited in their closed configuration by the circumference of the vehicle. Thus for a given static stability, drag is generally higher than for more conventional fin stabilisers. In an attempt to ameliorate this problem the most recent design, the MkIV WAF, has only six fins, as depicted in figure 1.

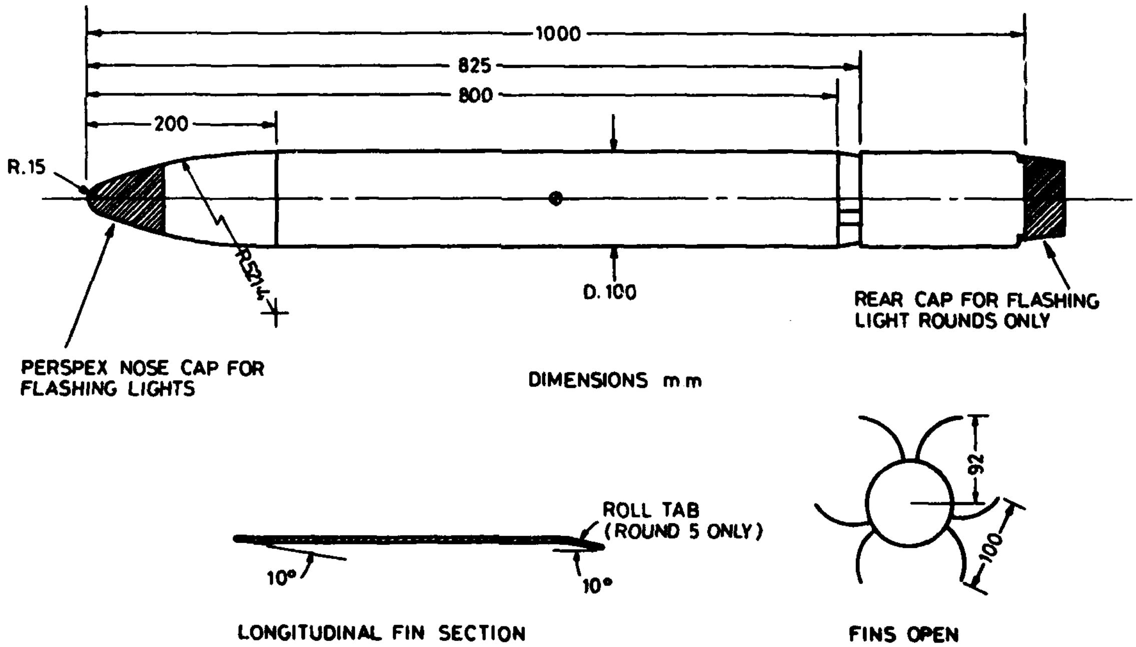

Figure 1. Schematic of vehicle

Reference 5 describes the results of the static wind tunnel tests of this configuration and this report describes the results of a series of five flight tests which were carried out as a follow up to the wind tunnel tests. The flight tests are described in detail in the next section. They were not all wholly successful but sufficient data was obtained for useful comparisons with wind tunnel results. The results are discussed in Section 3. Finally, Section 4 summarises the conclusions which have been drawn from the tests.

2. TRIALS OBJECTIVES AND RESULTS

The five vehicles were launched from the 385 mm gas gun on the WSRL gas gun range. All were launched at the same nominal conditions, an elevation of 12.5° and velocity of 130 m/s. The launch velocity was limited by safety requirements for range boundaries rather than the capabilities of vehicle or gas gun. Each vehicle was set in a tube in the sabot with its fins folded as shown in figure 1. The tube was arranged in the sabot so that the vehicle emerged with a nose up incidence of 4°. Initially only four firings were planned. Two were day firings to demonstrate separation from the sabot, opening of the fins, and to measure roll behaviour. The other two were night firings using the double flashing light technique described in reference 6, in which camera records of flashing lights carried in the nose and tail of the vehicle provide trajectory and attitude history of the vehicle. This data can be analysed, using a parameter estimation method, to obtain the basic, linear aerodynamics of the vehicle. The first night firing did not satisfy the main objectives of the trial and the trial was repeated so that five vehicles in all were fired. The objectives of each firing and the results obtained from that firing are discussed in detail in the following subsections.

2.1 First trial

The first vehicle was completely uninstrumented. The aim of the firing was to verify that the vehicle emerged from the sabot satisfactorily, the fins opened and the vehicle flew stably, exhibiting no gross flight dynamic instabilities. The only ground instrumentation was a WREFIP camera, which was positioned to photograph the separation of the vehicle from the sabot and deployment of the fins. Due to an error in processing the film, no information was obtained from the camera. However, the vehicle was observed to separate from the sabot and fly stably, and it impacted within the expected area. Thus the aims of the trial were achieved in broad outline although the information obtained was not as detailed as originally intended.

2.2 Second trial

The second trial was a night firing. The vehicle carried two flashing lights, arranged as shown in figure 1. The experimental method is described in detail in reference 6. Good quality trajectory data was obtained from the nose light and analysis of this provided an estimate of the drag coefficient. The nose trajectory data was fitted by parameter estimation using a simple particle trajectory model, from about 2.5 s after launch, until impact. During this period the oscillations from the initial disturbances have largely damped out and there will not be any significant contribution to the drag from incidence induced effects. Therefore the value obtained, $C_D = -0.290$, should correspond to the zero incidence drag.

Unfortunately, owing to the combined effects of poor quality camera plates, obscuration of the light by the fins and spreading of the light by the tail cone very few tail light images were recorded on the ballistic camera plates. Insufficient tail points were obtained to provide adequate data for analysis. Therefore no aerodynamic coefficients other than the zero incidence drag were obtained. This trial was repeated as the fourth trial of the series, using good quality camera plates and a tail cone with a reflective surface on the inside rear face.

2.3 Third trial

The third vehicle was fired during the day. The vehicle carried a magnetometer to measure roll behaviour, as the only on-board instrumentation. A WREFIP camera was used to photograph the launch, separation and fin deployment. Satisfactory records were obtained from the magnetometer and from the WREFIP camera. The magnetometer records showed no significant roll. This result bears out the wind tunnel measurements showing only small induced rolling moments which averaged to zero over one complete roll cycle. The WREFIP records showed a satisfactory launch. The vehicle emerged from the sabot and the fins deployed as expected.

2.4 Fourth trial

This trial repeated the earlier firing of a vehicle containing two flashing lights. Much better coverage of the tail light trajectory was achieved with this vehicle, due mainly to the improved quality of the camera plates. However, the coverage from each camera was not consistent and many different combinations of the five ballistic cameras had to be used to obtain a complete trajectory. Inconsistencies between cameras and large error residues for different cameras at different times tended to compound the problems so that the differencing of nose and tail positions to obtain attitude angles resulted in high noise levels in the data and spurious oscillations particularly for the azimuth data. However, some estimates of the aerodynamic coefficients were possible and they are listed in Table 1 together with rms errors in each. In this particular case, because of the inconsistencies between different cameras, the estimated rms errors in $C_{z\alpha}$, $C_{m\alpha}$ and C_{mq} are not reliable and the errors could in fact be much larger.

Detailed examination of the data indicates that the estimated error in C_x may be more reliable.

TABLE 1. ESTIMATED AERODYNAMIC COEFFICIENTS

Trial	C_x (2)	$C_{z\alpha}$	$C_{m\alpha}$ (1)	C_{mq}	$C_{np\alpha}$
2 rms	-0.290 0.001	-	-	-	-
4 rms	-0.270 0.005	-5.9 0.5	-8.9 0.2	-660 53	-
5 rms	-0.269 0.003	-9.5 1.1	-20.6 0.2	-360 80	73 13

(1) Moment reference is 5.0 calibres aft of the nose

(2) Reynolds number, based on body diameter, is about 8×10^5

(3) $C_{m\alpha}$, $C_{z\alpha}$, C_{mq} and $C_{np\alpha}$ are based on angular measurements in radians.

2.5 Fifth trial

The fifth and final trial again involved a double flashing light vehicle and the quality of the data was exceptionally good, due mainly to the improved quality of the camera plates. All flashing light images from both lights were well defined and the residuals from the least squares solution for position were small, indicating a high degree of accuracy and consistency in the data. As well as the flashing lights this vehicle carried a magnetometer to measure roll rate. Roll tabs were mounted alternately on three of the six fins, to produce a rolling moment. A longitudinal section of one of the fins, showing a roll tab, is given in figure 1. The resulting roll rate history is shown in figure 2. A simple model of the rolling moments was used to derive basic rolling moment coefficients from the data by parameter estimation. The roll acceleration was assumed to be given by

$$\dot{p} = (QSd/I_x)\ [C_l + C_{lp}(pd/2V)]$$

where C_l represents the rolling moment coefficient and C_{lp} represents the roll damping derivative. The other symbols are defined in the list of notation at the end of the text. Table 2 lists the values derived for the rolling moment coefficients. The relatively large value of C_{lp} shows that the fins are very effective for roll damping. The values of the other aerodynamic coefficients derived from the flashing light trajectory and attitude data are given in Table 1. The flashing light data was limited to the first three seconds of flight. The lights were turned off at this point on the trajectory to enable us to use the last flash as a reference point to synchronise the camera records of the flashing lights with the flash pulses superimposed on the magnetometer record. The first flash cannot be used to synchronise the two data sources because it does not appear consistently on the camera records. No degradation of the trials results is anticipated because the release disturbance has largely damped out by this time. The high quality of the flashing light trajectory data and the general consistency of results can be regarded as an indication of the reliability of the results obtained.

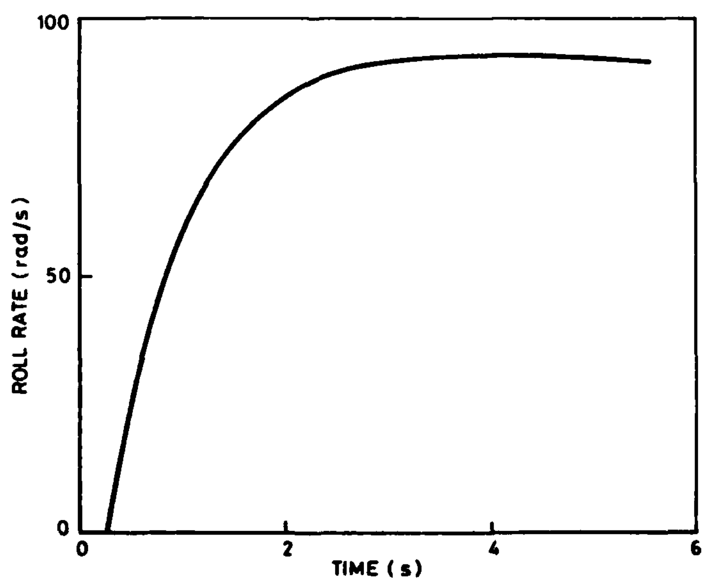

Figure 2. Roll history of round 5

TABLE 2. ROLLING MOMENT COEFFICIENTS

	C_l	C_{lp}
Round 5	0.209	-5.42
rms	0.0001	0.002

3. DISCUSSION

We look first at the two daylight firings. On both trials only basic instrumentation was used and the objects of the firings were achieved. These firings demonstrated that this six finned WAF design could be launched from a tube, that the fins deployed satisfactorily on emerging from the tube, and that the vehicle then flew stably without exhibiting any unexpected flight dynamic behaviour. The magnetometer record obtained from the second daylight firing provided verification of the low rolling moments measured in the wind tunnel.

Before considering in detail the aerodynamic coefficients derived from the double flashing light rounds, we look briefly at the statistics of the apparent distance between the two flashing lights. Since the physical distance between the lights remains constant throughout the flight, the scatter of the apparent distance between them, according to the camera records, provides a good measure of the quality of the data. Standard deviations measure generally between 0.02 m and 0.03 m, occasionally less than 0.02 and very rarely more than 0.04 m. Mean value of the apparent distance between lights and the standard deviation about the mean, are listed for each trial in Table 3. The mean values are consistent, indicating that there are no severe anomalies in the data. The standard deviations, on the other hand, vary widely. The value of 0.029 m for the second trial is within the expected range; however, very few tail points were measured so that detailed data analysis was not possible. Trial 4 produced a standard deviation of 0.084 m, which is abnormally high so that results from this trial are not very reliable. Finally, the standard deviation of 0.020 m for the last trial is evidence of the high quality of the data from this trial.

TABLE 3. APPARENT DISTANCE BETWEEN THE NOSE AND TAIL LIGHTS

Trial	Mean (m)	Standard Deviation (m)
2	0.977	0.029
4	0.970	0.084
5	0.975	0.020

Typical static wind tunnel results from reference 5 are listed in Table 4, giving values at low incidences for $C_{m\alpha}$ of -21.4 and for $C_{z\alpha}$ of -10.6. Since more than 95% of all data points from flight trials showed incidences below 4°, we expect these low incidence results should compare well with the flight values given in Table 1. The results from trial 5 do in fact agree very well with the wind tunnel measurements. Unfortunately, the results from trial 4 do not agree and we are forced to conclude that these results are not credible, probably due to the very poor quality of the trajectory data, for both nose and tail lights, but particularly for the tail light.

TABLE 4. STATIC WIND TUNNEL DATA, M=0.5

α(degree)	$C_x^{(3)}$	C_z	$C_m^{(1)}$	$C_D^{(2)}$
0	-0.238	0.	0.	0.238
2	-0.223	-0.371	-0.749	0.236
4	-0.199	-0.771	-1.623	0.252
6	-0.171	-1.197	-2.585	0.295
8	-0.161	-1.672	-3.681	0.392
10	-0.157	-2.158	-4.859	0.529

NOTES:- (1) Moment reference point 5.0 calibres aft of the nose

(2) $C_D = -C_x \cos\alpha - C_Z \sin\alpha$

(3) Reynolds number, based on body diameter, is $R_d = 2.0 \times 10^5$

The results for the axial force coefficient show anomalies which cannot be properly explained by the poor quality of the data from trial 4. The values of drag coefficient and the values of axial force coefficient which were measured in the wind tunnel are shown in Table 4. There is a significant variation of axial force coefficient at low incidence, and this may to some extent account for the variation in the free flight results. In order to compare free flight and wind tunnel results, it is necessary first to adjust for the different Reynolds numbers. In addition, the wind tunnel results do not include body base contribution to the axial force, which is estimated to be about -0.08 at zero incidence, and this must also be allowed for. We estimate that skin friction contributes about 75% to the axial force measured in the wind tunnel. Therefore, assuming that the skin friction coefficient

$$C_f \propto (\log Re_d)^{-2.45},$$

wind tunnel measurements adjusted for Reynolds number and base presure effects give $C_x = -0.28$ at 0° incidence, decreasing to $C_x = -0.25$ at 4° incidence.

The values obtained from the free flight trials are less widely spaced so that the sensitivity of the axial force coefficient to incidence variations may account for the discrepancies in the free flight results. By looking at the axial force coefficient results for each of the three flashing vehicles in turn, it becomes apparent that the variation in results can be explained in terms of this sensitivity. Firstly, the result for round 2 was obtained using data from 3 s after launch until impact when the incidence was very close to zero. This round yielded the value of -0.290, which is at the top end of the range and is therefore consistent with wind tunnel results. Secondly, the result for round 4 used data from the whole of the trajectory, so that a large part, but not all of the data is for incidences close to zero. The value of -0.270 obtained from round 4 is closer to the middle of the range. Thus, it is also consistent with the wind tunnel results. Finally, round 5 data, covered only the first 3 s of flight, when the incidence was generally between 1° and 4°. The result of -0.269, includes a contribution of approximately 7% from the roll tabs on the fins. The remainder, -0.250, fits in at the bottom of the range as would be expected. Thus, wind tunnel and free flight measurements of the axial force are consistent. The apparent variation in free flight results is probably due to the variation in the range of incidence covered by the different sets of data.

The flight test measurements are particularly useful because the wind tunnel measurements provided static data only. Thus, no comparisons can be made for the measurements of the dynamic derivatives C_{lp}, C_{mq} and $C_{np\alpha}$. However, a few general comments can be made about the values measured for the dynamic derivatives. The value of the pitch damping derivative, C_{mq}, obtained from trial 4 is unlikely to be reliable, bearing in mind that the other derivatives are inaccurately determined. However, the value given by the last trial should be fairly well determined. Past experience indicates that the rms error tends to be an overestimate. This value, -360°, suggests an improvement of about 50% in pitch damping compared with the eight finned MkIII WAF(ref.3), which is consistent with the overall improvement in efficiency of the fins. The Magnus moment derivative was surprisingly well determined from the data obtained during the last trial, in view of the fact that the incidence was less than two degrees over the whole period for which the roll rate was more than 50% of its equilibrium value. Near the equilibrium roll rate the Magnus moment $C_{np\alpha}(pd/2V)\alpha$ can be evaluated to give 2.7α, so that Magnus moment is about 13% of the restoring moment. The effect of the Magnus moment can be seen in figure 3, where the vehicle continues to precess about the zero incidence point with an amplitude of about 1.5°, after the effects of the initial motion have become completely damped. The low amplitude precession continued throughout the flight, and analysis indicates that it is entirely due to the Magnus moment. Finally, the rolling moment coefficients indicate how easily the roll of the vehicle can be controlled. The large roll damping is due to the effectiveness of the fins and provides the capability for quite delicate control of roll rate. The high roll rate generated by the relatively simple roll tabs could also be a useful characteristic of a tube launched rocket.

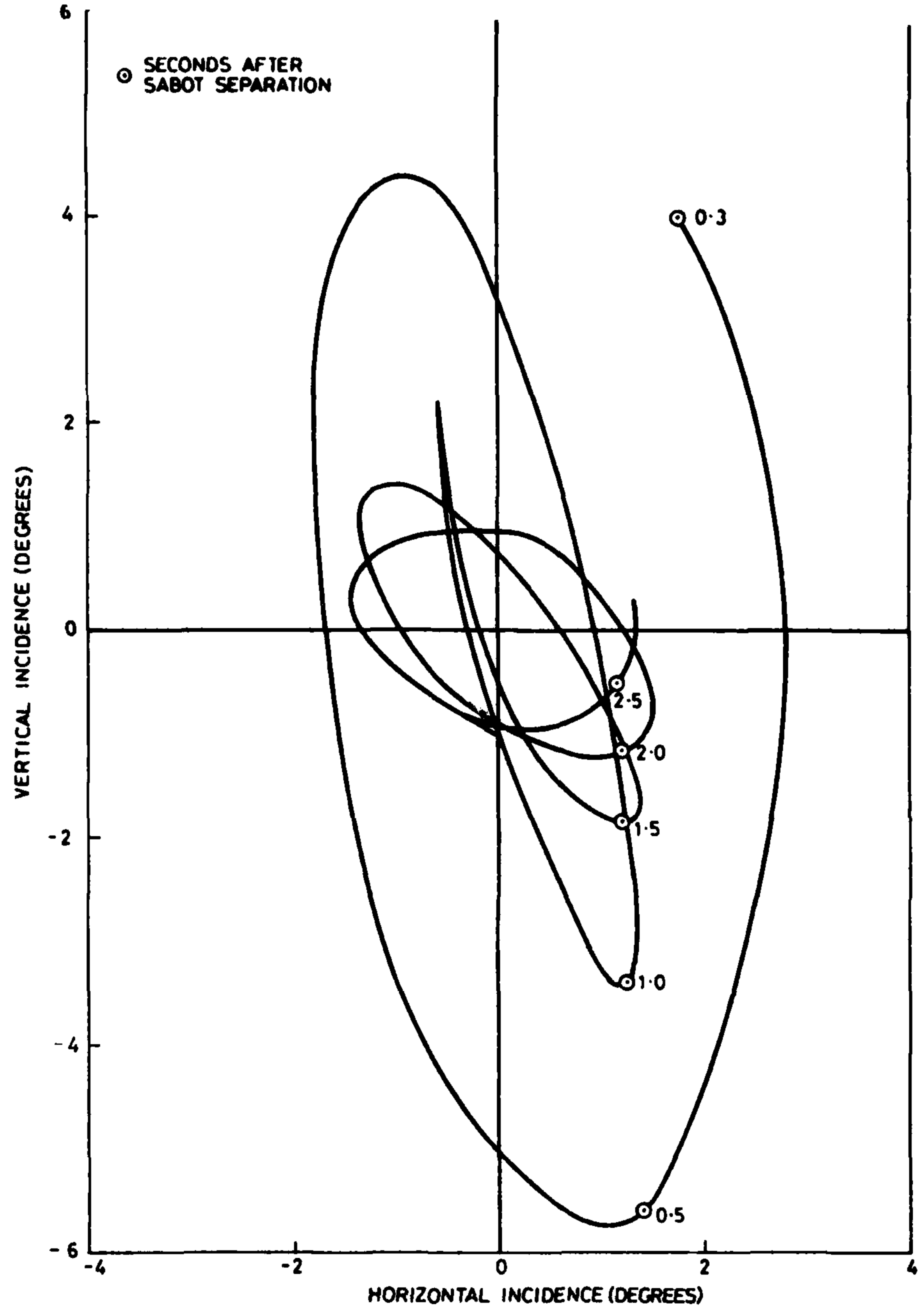

Figure 3. Incidence behaviour of round 5

4. CONCLUSIONS

A series of five flight trials of the MkIV six finned WAF design have been carried out, using the WSRL gas gun range. None of the vehicles exhibited any anomalous flight behaviour of the sort which might detract from the performance of the MkIV WAF when used as a stabiliser for tube launched rockets. The two vehicles which were fired during the day showed satisfactory separation from the sabot tube and deployment of the fins. There was no appreciable separation disturbance. The magnetometer record obtained from the second daytime firing corroborated the wind tunnel predictions of very low rolling moments for the vehicle with unmodified fins.

The results from the night firings were disappointing with complete results obtained only from the last trial. The static aerodynamic coefficients obtained in this trial agreed well with wind tunnel results. Valuable estimates were also obtained for three dynamic derivatives. The roll damping and pitch damping are both greater than for the eight finned MkIII wrap around fin configuration, and are consistent with the observed improvement in efficiency of the fins. The vehicles showed consistently high static and dynamic stability.

There was considerable variation in estimated values for the axial force coefficient. A possible explanation of this variation lies in the different incidence ranges covered by the data from each trial, coupled with the sensitivity of axial force to incidence variations, which is demonstrated by the wind tunnel results. Base pressure is also affected by incidence, but changes in the total axial force coefficient due to this effect will be relatively small. After allowing for the different Reynolds number of flight and wind tunnel tests and including an estimated base pressure contribution for the body, wind tunnel and free flight results are generally consistent. Thus in all cases where comparisons can be made there is general agreement between wind tunnel and flight measurements.

5. ACKNOWLEDGEMENT

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NOTATION

C_D	drag coefficient
C_l	rolling moment coefficient due to roll tabs
C_{lp}	$\partial C_l/\partial(pd/2V)$, derivative of roll damping moment coefficient
$C_{m\alpha}$	$\partial C_m/\partial\alpha$, derivative of static pitching moment
C_{mq}	$\partial C_m/\partial(qd/2V)$, derivative of pitch damping moment coefficient
$C_{np\alpha}$	$\partial^2 C_n/\partial\alpha\partial(pd/2V)$, derivative of Magnus moment coefficient
C_x	axial force coefficient
$C_{z\alpha}$	$\partial C_z/\partial\alpha$, derivative of normal force coefficient
d	body diameter, used to non-dimensionalise aerodynamic moments
I_x	vehicle roll inertia
p	vehicle roll rate
Q	$\rho V^2/2$, dynamic pressure, used to non-dimensionalise aerodynamic forces and moments
q	vehicle pitch rate
S	body cross-sectional area, used to non-dimensionalise aerodynamic forces and moments
V	true air velocity of vehicle
α	total incidence of vehicle
ρ	air density

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